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Sensitivity of Wave Energy to Climate Change

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***Abstract*—Wave energy will have a key role in meeting renewable energy targets en route to a low carbon economy. However, in common with other renewables, it may be sensitive to changes in climate resulting from rising carbon emissions. Changes in wind patterns are widely anticipated and this will ultimately alter wave regimes. Indeed, evidence indicates that wave heights have been changing over the last 40 years, although there is no proven link to global warming. Changes in the wave climate will impact on wave energy conversion. Where the resource is restricted there may be reductions in energy exports and consequently negative economic impacts. On the other hand, increased storm activity will increase installation survival risks. Here, a study is presented that, for the first time, indicates the sensitivity of wave energy production and economics to changes in climate.**

***Index Terms*—Wave energy, meteorology, oceanography, climate change, power generation economics.**

I. Introduction

WAVE energy has a key role to play in meeting long-term renewable energy targets as part of the drive to a low carbon economy. This is particularly true in the United Kingdom which possesses vast wave energy resources with the most favourable sites located off the Scottish west coast. With mean wave power in excess of 60 kW per metre of wave front, Scotland's offshore wave power potential is estimated at 14 GW and could provide some 45 TWh/year [1].

While wave energy is being developed in order to limit or avoid climate change, its reliance on the natural environment means that it may be vulnerable to changes in climate that result from rising carbon emissions. It shares this risk with other renewable sources such as hydropower [2] and wind [3]. Indeed, there is a growing body of evidence that indicates that global wave heights have been changing over recent decades and while it has been suggested that this may be caused by global warming [4], there is no conclusive proof as yet.

Given the prospects for wave energy to provide clean energy in many parts of the world, there is a need to identify and quantify the potential for climate change to alter the wave energy resource and the ability of wave energy devices to extract energy on a commercial basis. This study is, the authors believe, the first to examine the sensitivity of wave energy to changes in climate.

Section II reviews literature relevant to changes in wave climate, while Section III describes the potential wave energy impacts. Section IV introduces key concepts and summarises current wave energy resource and production appraisal methods. Section V outlines an alternative method that uses projections of future atmospheric climate variables, like wind speed, to infer the wave resource. It is then applied to a case study to quantify the sensitivity of wave energy conversion to changes in climate. The final section discusses the suitability and limitations of the approach.

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II. Changing Marine Climate

Trends of increasing wave height in the north east Atlantic were identified in the late 1980s and early 1990s [5-6]. These suggested increases in mean wave height of some 2% per year and are in line with other sources that indicate changes of 30-50% over 30 years. More recent studies have identified similar changes in the Pacific [7]. Early studies [6] were unable to identify trends in local wind speed that would correspond to increased wave heights. There was recognition that local wave conditions are a more complex blend of local and distant wind activity [8]. Further investigation aimed to explain the wave changes from broader climate conditions; a connection between wave heights and the longitudinal atmospheric pressure gradient in the North Atlantic was found [8].

Much of this work was based on in-situ data from buoys and weather ships. A combination of poor spatial coverage, relatively few long-term series and changes in observational practice meant that identification of underlying changes in weather patterns from this data is difficult [9]. Two approaches have been applied to circumvent these problems:

1. Wave 'hindcasting'
2. Satellite altimeter measurements

Hindcasting uses wind-wave models driven by historic weather data to develop a past history of wave climate. Notable examples include the WASA Group study [10] which also projected future wave climate using data from a climate change experiment albeit with inconclusive results.

Satellite altimeter data has been used extensively in constructing wave climatology. One approach [9] noted correlations between the variability of wave height and the North Atlantic Oscillation (NAO) which plays a key role in northern hemisphere climate patterns.

To date, there has been no investigation into the impacts of changes in wave climate on wave energy conversion.

III. Potential Wave Energy Impacts

Changes in wind patterns are a widely anticipated consequence of climate change. Projections suggest that the continental United States will see onshore wind speed reductions of 1 to 3.2% over the next 50 years, although there is a great deal of uncertainty [3]. It is likely that offshore winds will also change, particularly given the long term trends in European wind speeds [11]; e.g. UK winter speeds have increased by 15-20% over the past 40 years. Ocean waves result directly from the action of wind across an expanse of water and, as shown by wave power relationships presented in Section IV, the wave energy resource is extremely sensitive to wind speed as it is proportional to the fifth-power of wind speed (e.g. a 5% change in wind speed would produce approximately a 25% change in wave power). As such, changes in wind patterns have potentially significant consequences for wave energy development (Fig. 1).

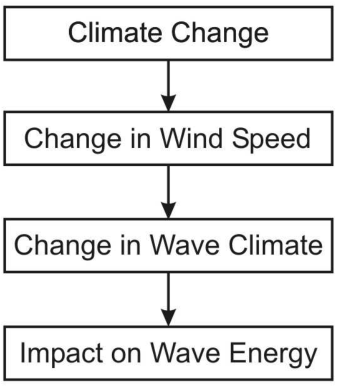

Fig. 1. Linking climate change and wave energy

In a manner similar to wind turbines, wave energy converters (WECs) are designed to capture energy within specific operational bands of wave height, period and direction. Although much research has focussed on developing 'tuneable' devices, changes in the resource will alter energy capture. Where the climate alters in such a way as to restrict the resource there may be reductions in energy production and consequent economic impacts, particularly where this coincides with high price periods. In cases where the wave resource increases it may bring revenue benefits although there is a likelihood that increased storm activity will pose an enhanced risk to the survivability of installations; installations will need to be designed with this in mind.

Sea level rise is frequently quoted as a result of climate change and it is expected that sea levels around the UK will increase by 20-80 cm by 2050. While WECs moored in deeper water might experience limited impacts, shoreline based devices could be affected by raised water levels.

In examining these impacts, an understanding of key concepts in wave energy appraisal is required.

IV. Wave Energy Appraisal

This section aims to summarise key concepts in wave energy and its appraisal. Further information on wave energy in general may be found in [12] or [13] while detail on the mathematics can be found in [14].

Wave energy can be considered as a concentrated form of solar energy. As winds flow over open bodies of water they transfer some of their energy to form waves. While the mechanisms are complex and not fully understood, three major processes are apparent [13]:

1. Air flow over the sea applies a tangential stress to the water surface leading to wave creation and development.
2. Turbulent air flow close to the water surface creates rapidly varying shear stresses and pressure fluctuations, causing further wave growth where these oscillations are in phase with existing waves.
3. Once waves have reached a certain size, the wind can create a stronger force on the trailing edge of the wave, resulting in further growth.

The energy transfer and, accordingly, the wave size depends on the strength and duration of the wind and the distance over which it blows (the fetch). During storms wave power levels may exceed 1 MW/metre of wave front.

While waves travel in given directions as a result of water particles moving in circular orbits, the particles themselves do not travel. A useful way of explaining the power flow across a given wave front is to visualise a water particle moving forwards at the height of the crest and returning at the level of the trough. In doing so the particle has transferred potential energy in the apparent direction of the waves and, given the motion of the wave train, the power flux across the wave front is evident. From this, it can be shown that wave varies with the square of the wave height and linearly with wave period (i.e., waves with larger amplitudes and wavelengths possess more energy) according to:

$$P = 0.49 {H_S}^2 T_e \tag{1}$$

where P is power (kW/m of wave front), and H_S and T_e are the significant wave height and wave energy period, respectively. They are values that are representative of the wide spectrum of waves apparent in real seas which possess different heights, periods and directions.

H_S is defined as four times the root-mean-square (RMS) elevation of the sea surface (H_{rms}):

$$H_S = 4H_{\text{rms}} = 4\sqrt{m_0} \tag{2}$$

where m_0 is the zeroeth moment (or variance) of the wave spectrum. Historically, H_S was defined as the mean of the largest one-third of waves (estimated by eye from sea vessels) but since the advent of in-situ and satellite measurements this has now largely been superseded by the RMS measure.

While there are several definitions for representative wave period in use, the energy period T_e is favoured for wave energy approaches as it weights waves by energy content [14]:

$$T_e = m_{-1}/m_0 \tag{3}$$

where m_{-1} is the reciprocal of the first spectral moment (the mean frequency).

Together the significant wave height and period allow a range of 'sea states' to be specified. Their joint probability of occurrence is often shown on scatter diagrams (often in parts per thousand) as Fig. 2 illustrates.

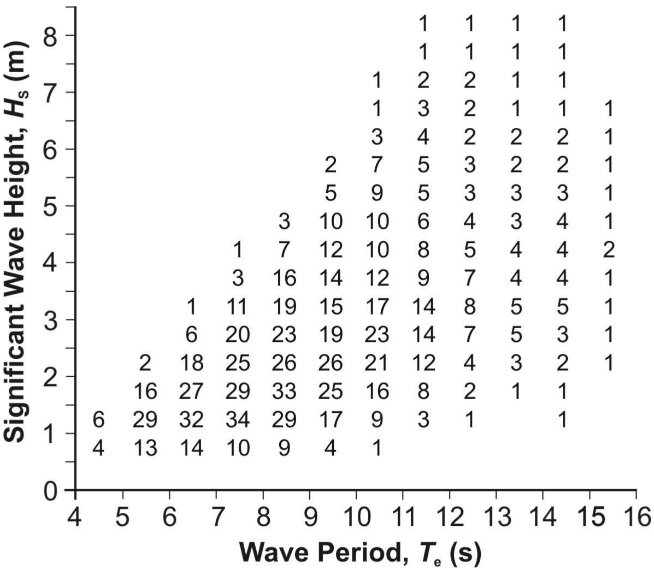

Fig. 2. Example scatter diagram (parts per 1000)

Appraisal of WEC output and economics is similar to that for other renewables and focuses on the available resource. A simplified version of the standard approach [13] is shown schematically in Fig. 3.

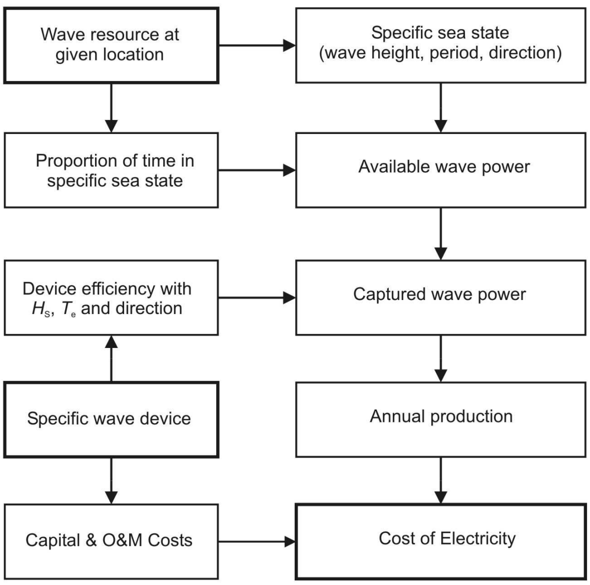

Fig. 3. Methodology for appraising wave energy converters, adapted from [13]

For the assumed location of the WEC, the wave resource record allows a range of applicable sea states to be identified. Each combination of H_S, T_e and direction will be applicable for a given portion of the year and will be weighted accordingly. For each sea state, the characteristics of an individual device will allow an estimate of capture efficiency and hence output. The weighted average of the output during each sea state provides the annual production. When combined with economic and pricing data the financial performance can be defined.

V. Climate Impact Modelling

The previous section indicated that current predictions of WEC production and economic performance are based on historic wave climate data. Given the potential for future change in the wave climate it may not be prudent to rely on historic data. Instead, projections of future atmospheric climate variables, like wind speed, could be used infer wave climate and WEC performance. This section outlines a method for doing this.

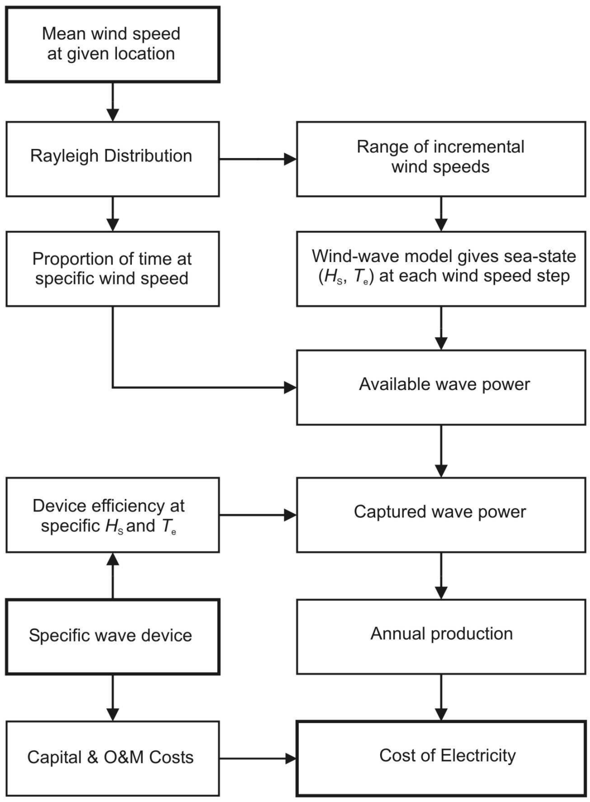

Fig. 4. Wind climate-dependent appraisal methodology

As noted in Section II several studies used the output from General Circulation Models (GCMs) to produce scenarios of future wave conditions. GCMs are complex atmosphere and oceans models, akin to weather forecasting models, albeit driven with scenarios of greenhouse gas concentrations. In inferring future wave heights with GCM data, studies used wind fields to drive wind-wave models or pressure data correlations between wave climate and atmospheric pressure (assuming that the relationships hold over time). One drawback of these approaches is that they are intensive computationally. Importantly, it is well known that GCM projections vary between models and, as such, multiple scenarios are required to estimate the range of future climate, making it difficult to infer future vulnerability.

In contrast, sensitivity studies are generally straight-forward, readily understood and are a common approach for initial investigations.

As a first attempt at indicating the degree to which wave energy conversion is influenced by climate change, its sensitivity to changes in mean wind speeds is assessed. This has been achieved by combining well-known wave and wind spectra to provide a link between wind climate and wave energy potential. The appraisal methodology, as adapted, is shown in Fig. 4.

A. Rayleigh Wind Speed Distribution

The Rayleigh distribution is a common and straight-forward approach for representing the wind resource. It is defined by the mean wind speed $\overline{U}$ [15]:

$$p(U) = \frac{\pi}{2}\left(\frac{U}{\overline{U}^2}\right)\exp\left[-\frac{\pi}{4}\left(\frac{U}{\overline{U}}\right)^2\right] \tag{4}$$

where U is a particular wind speed and $p(U)$ the probability of its occurrence. When modelled with incremental values of wind speed U_i, (4) gives the probability of occurrence for each increment. Hence, for a given period, this equates to the duration of time (in hours) for which each wind speed step is experienced.

B. Wind-Wave Model

The Pierson-Moskowitz (PM) spectrum [16] describes a fully-developed wind-created sea, i.e., one in which wind that has been blowing over a long enough time (6-18 hours) and distance (200-600 km) to allow the sea to reach a steady state condition. The spectrum is empirically derived and uses the wind speed, U_0 (at a height of 19.5m above mean sea level) as the single parameter that defines the energy spectrum [16]:

$$S(\omega) = 0.0081 g^2 \omega^{-5} \exp\left[-0.74\left(\frac{g}{U_0 \omega}\right)^4\right] \tag{5}$$

where $S(\omega)$ is the spectral energy as a function of frequency ω (rad/s). Fig. 5 shows a plot for an 8 m/s wind speed.

While (5) appears rather unwieldy, the sea-state can be given by analysis of the spectral moments using (2) and (3). H_S and T_e are related to wind speed by [14]:

$$H_S = 0.0212 \cdot U_0^{\,2} \tag{6}$$

$$T_e = 0.625 \cdot U_0 \tag{7}$$

Use of (6) and (7) allows the specification of both significant wave height and wave period (and using (1) power) for any given wind speed. Across a range of wind speeds this generates a single curve on an scatter diagram as Fig. 6 shows.

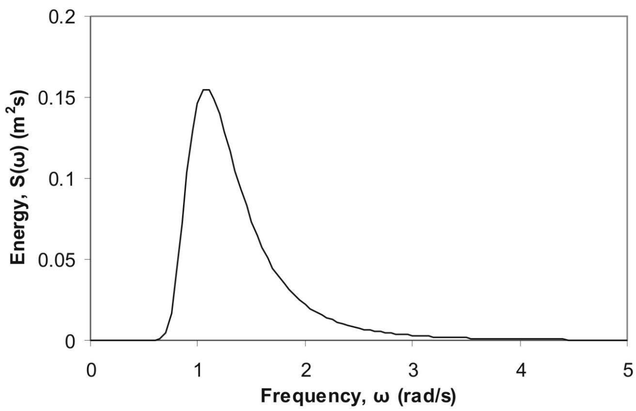

Fig. 5. Pierson-Moskowitz spectrum for wind speed of 8 m/s

Clearly, the PM spectrum, in common with other spectra developed for wind-wave modelling, does not fully capture the range of combinations of H_S and T_e that are possible. However, they are accepted as being reasonable approximations given the relative paucity of data and feature heavily in wave power research.

In itself the PM spectrum is not sufficient for inferring changes as particular wind speeds and accordingly, wave heights/periods exist for only a fraction of the year. A fuller representation of the range of conditions is achieved by combination with the wind speed distribution.

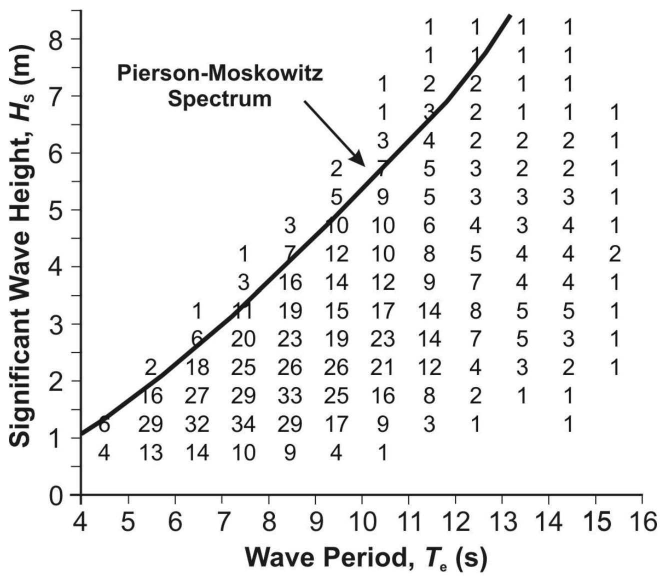

Fig. 6. Pierson-Moskowitz spectrum superimposed on scatter diagram.

C. Combined Wave Energy Distribution

To draw together the wind and wave spectra, each incremental value of wind speed is taken to be equal to that required by the PM spectrum to define the sea state, i.e.

$$U_{0,i} = U_i \tag{8}$$

As such, there will be a series of wave height/period pairs and, by definition, wave powers covering the wind speed range. The implicit assumption is that the Rayleigh-modelled wind speeds persist for the minimum time required for fully developed seas. This is reasonable for a first approximation.

Alteration of the mean wind speed specifying the Rayleigh distribution will not alter the magnitudes of the wave power as these are fixed by the incremental wind speed value. Rather, the probability of each sea state and power level will change, altering the hourly duration and energy output over the period.

Summation across all wind speed increments provides the total wave energy available. Combining this information with device-specific efficiency and economic information will provide estimates for production and economic performance. In this way, the alteration of mean wind speed by defined amounts will provide a means of examining the sensitivity of wave energy conversion to changes in climate.

VI. CASE STUDY: SCOTTISH WEST COAST

The case study focuses on the wave climate off the west coast of Scotland as WECs will eventually be deployed here. The assessment method set out in the previous section was implemented in spreadsheet form. For each 0.25 m/s increment in wind speed (over the range 0 to 30 m/s), the probability of occurrence and duration were calculated from (4). Equations (1)-(3) and (6)-(7) then provided H_S, T_e and wave power, which were then combined to estimate annual wave climate.

A. Wind Resource

The mean annual wind speed (at 19.5m) was estimated at 10 m/s based on data in [17] for a point in the Atlantic at 54°N, 22°W. While this lies somewhat to the west and south of the Scottish coast, it is a representative value as the PM spectrum assumes the same wind speed across the full fetch.

B. Wave Energy Converter

There are a wide range of WECs at different stages of development, each with specific operating characteristics and wave response. For the purposes of illustration, a WEC developed by Ocean Power Delivery Ltd is examined here.

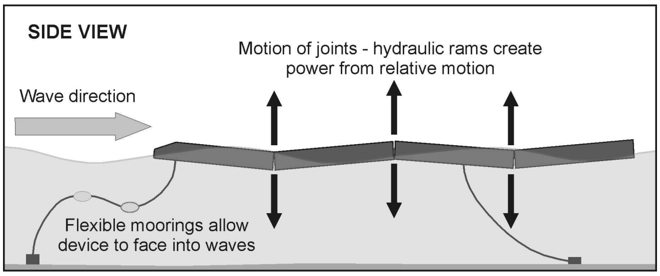

Fig. 7. Side view of Pelamis wave energy converter, adapted from [18].

The Pelamis [18] is a semi-submerged snake-like device (the name means sea-snake) consisting of four articulated cylindrical sections linked by hinged joints (Fig. 7). The joints move as waves run down the length of the device and the relative motion of the sections is resisted by hydraulic motors which pump high pressure fluid through hydraulic motors to drive induction generators. The WEC is self-referencing in that it always faces into the waves and so the lack of directional information is not an issue. Recently deployed, the full-scale 750 kW prototype is 120m long and 3.5m in diameter.

The Pelamis is designed to maximise production in normal sea conditions whilst ensuring survival in heavy seas (i.e. H_S > 8m) through power limitation. The power output matrix in Fig. 8 gives the device output as a percentage of capacity for combinations of H_S and T_e. The black line corresponds to the PM spectrum; the nearest grid cell values are assigned to the relevant sea state/wind speed increment.

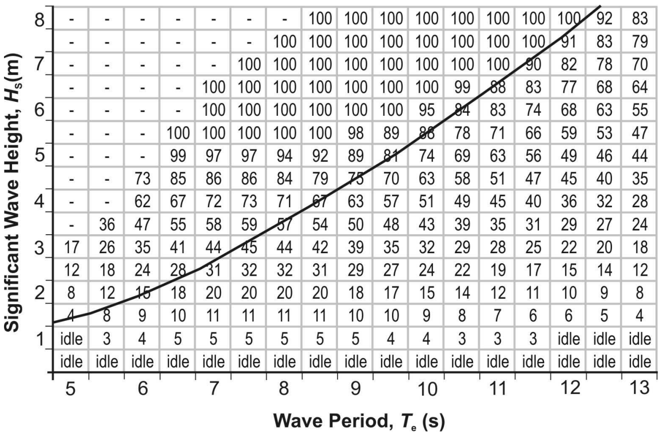

Fig. 8. Power matrix for Pelamis (% of capacity) [18] and PM spectrum.

The cost of such a device is commercially sensitive, so representative capital and recurring costs were estimated based on costs for other wave devices [13]. Here, the WEC is costed at just under £1 million per unit with annual operations and maintenance costs (O&M) set slightly higher than would be expected for wind turbines. Revenue is assumed to accrue from sales of energy as well as Renewables Obligation Certificates (ROCs) of which UK suppliers are obliged to purchase a minimum level. This data is given in Table I.

TABLE I
ASSUMED COST AND REVENUE DATA

Item	Value
Capital cost (£/kW installed)	1300
Annual O&M (% of capital cost)	2.5
Economic Lifetime (years)	30
Revenue, Energy + ROC (£/MWh)	60
Discount rates applied (%)	8 and 15

C. Base Case Performance

The Base Case represents the range of sea-states and resultant device technical and economic performance that arise from the mean wind speed of 10 m/s (Table II).

TABLE II
MODELLED WAVE ENERGY AND DEVICE PERFORMANCE

Measure	Value
Mean wave height, H_S (m)	2.70
Mean wave period, T_e (s)	6.25
Mean available wave power (kW/m)	83.73
Mean power output (kW)	232.80

Production (GWh/yr)	2.04
Load factor (%)	31.0
Idle time (%)	34.8
At capacity (%)	4.9
Internal Rate of Return, IRR (%)	9.36
Unit cost (p/kWh), 8% discount rate	5.44
Unit cost (p/kWh), 15% discount rate	8.48

The modelled weighted average significant wave height and period and the available wave power are in line with expected values for the North Atlantic albeit on the low side (mean wave power of 83 kW/m compared with the 91 kW/m given in [19]).

The resulting production and average power output are reasonable estimates albeit once again on the low side. This can be seen with the load factor being at the lower end of the range expected for such a device. It can be seen that the time during which the device is idle is around one third of the year, while peak output is achieved for only 5% of the year.

Given the assumptions made, the economic performance is in line with expectations for this non-mature technology and with an electricity cost in the region of 5 to 6 p/kWh it is nearing cost competitiveness.

D. *Climate Sensitivity*

Changes in marine climate were simulated by altering the mean annual wind speed by up to ±20% in 10% intervals. A summary of the changes to wave estimates and device performance is given in Table III.

TABLE III
SUMMARY OF CHANGES WITH WIND SPEED VARIATION

Measure	**Annual mean wind speed change**			
	-20%	-10%	10%	20%
Mean H_S (m)	1.73	2.19	3.27	3.88
Mean T_e (s)	5.00	5.63	6.88	7.50
Mean wave power (kW/m)	27.5	49.5	134.4	205.6
Mean output (kW)	134.4	183.8	279.4	322.5
Production (GWh/yr)	1.18	1.61	2.45	2.83
Load factor (%)	17.9	24.5	37.3	43
Time at idle (%)	48.7	41	29.7	25.7
At capacity (%)	0.9	2.4	8.2	12.2
IRR (%)	2.45	6.18	12.16	14.63
Unit cost (p/kWh), 8%	9.43	6.89	4.54	3.93
Unit cost (p/kWh), 15%	14.68	10.74	7.06	6.12

1) *Wave climate*

Fig. 9 shows the variation in mean wave height period and wave power with the above range of wind speed changes. Wave period varies in direct proportion with the wind speed while wave height is more sensitive to increases in speed as might be expected from the square-relationship. The 20% rise in wind speed appears to raise mean wave heights by around 44% (>1m). The combined effect of changes in wave characteristics on available wave power is significant with the power relationship ($P \propto U^5$) clearly visible. For example, the 20% fall lowers power levels by two-thirds while the opposite change raises them by four-thirds.

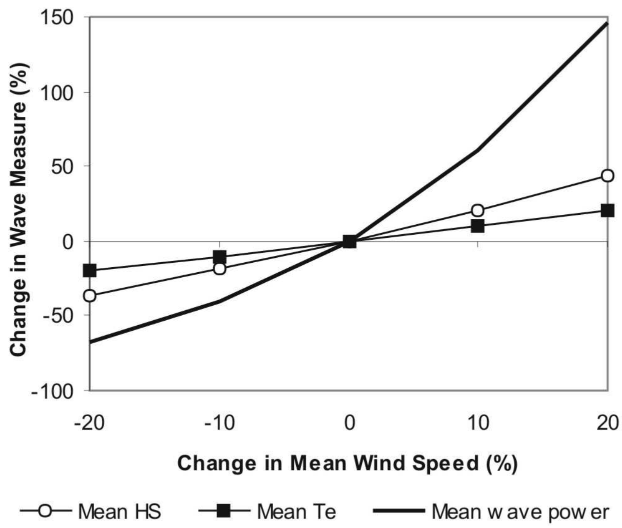

Fig. 9. Mean wave height, period and power with mean wind speed change

2) *Production*

Such sensitivity to wind speed has a major effect on the performance of the wave device (Fig. 10), albeit tempered by its ability to shed excess power. Clearly, output is positively related to wind speed; it is rather sensitive as energy production varies by up to 800 MWh/yr for a 20% wind change. This is apparent in both the mean power level and the load factor.

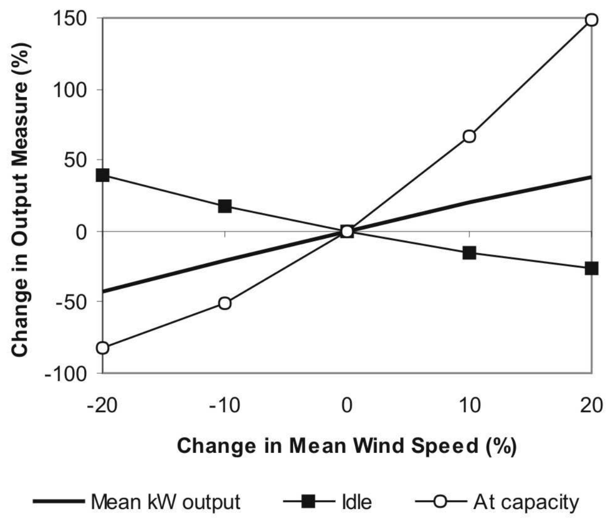

Fig. 10. Mean power output, time at idle/capacity with mean wind speed change

The device shows slightly greater sensitivity to falling wave powers as the much larger change in idle time indicates. Increases in wind speed have less effect as wave powers in excess of rating are shed. This is illustrated by the proportion of time at maximum output: under the conditions suggested by a 20% increase in mean wind, this duration increases to 12%; it drops to less than 1% under the opposite scenario.

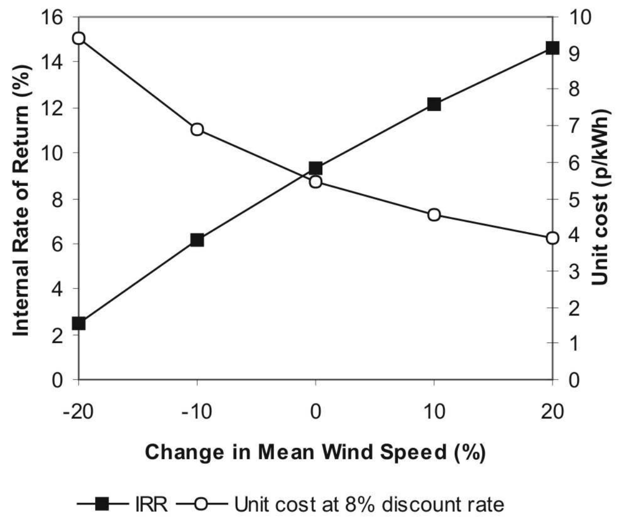

Fig. 11. Variation in economic indicators with mean wind speed change

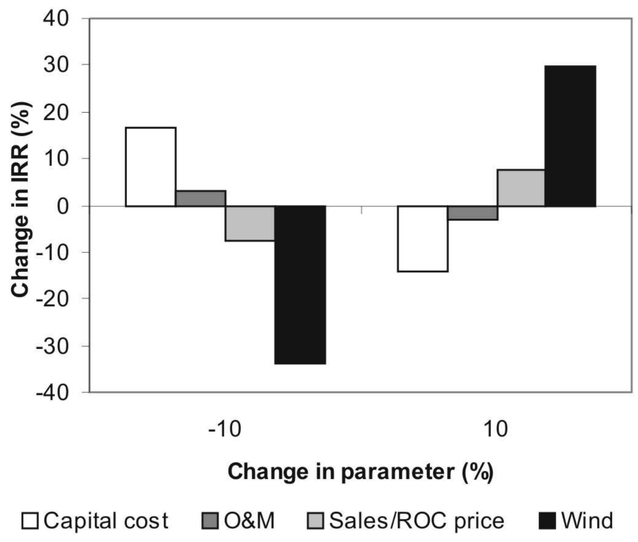

Fig. 12. Sensitivity of IRR to key project variables

3) Economics

The large changes in production, and in consequence, revenue have a significant impact on the economics of the device (Fig. 11). The range of Internal Rate of Return (IRR) values covers 12 percentage points and, following the production pattern, shows greater sensitivity to falling mean wind speed. Unit electricity costs show significant variation with a 75% increase under the -20% scenario.

4) Wind Sensitivity in Context

In order to set the climate sensitivity results in context, the impact of changes in risk factors that will affect wave energy projects were examined. This allowed a comparison of the sensitivity of the project to changes in wind speed relative to other key project parameters: capital costs, O&M costs and sales/ROC prices. Each parameter was altered, in turn, by ±10% of its original value and the value of IRR examined for the base wind conditions.

The IRR results from these tests are shown in Fig. 12 along with the equivalent results for wind speed changes. The sensitivity to wind changes is almost twice that for the next nearest parameter, capital cost, with Sales/ROC prices and O&M a good way behind. As IRR is the discount rate at which project value is zero, the sensitivity of IRR to discount rate is not meaningful. However, calculations with cost of energy suggest that the sensitivity is less than for capital cost.

Overall, this comparison adds credibility to the view that changes in wind climate should be of concern for those developing, deploying and relying on wave energy devices.

VII. Discussion

The authors believe that this study is the first to address how global warming-induced changes in wind climate will influence the production and economics of wave energy devices. A deliberately simple approach has been taken in order to get a quantitative appreciation of the potential changes. As a result, several important aspects are not considered:

1. Swell and monthly variations in wave climate,
2. Survivability in extreme waves, and
3. Sensitivity of alternative WECs.

The Pierson-Moskowitz spectrum takes into account only wind generated waves and ignores swell. Swell waves are larger, longer wavelength waves produced by distant extra-tropical cyclones (storms). The intensity and frequency of these storms are of major importance to the wave energy resource of Western Europe and the Pacific Northwest, particularly in the winter months. In the North Atlantic and Pacific the storm tracks tend to move in a north-easterly direction and, as the storm rotates anti-clockwise, the southern part of the system continuously feeds energy into the waves. With the storm effectively moving with the waves, very large energetic waves are produced. When the storms weaken, the waves continue to travel (with minimal energy loss) in a north-easterly direction, arriving as swell a few days later. By ignoring swell, the PM spectrum tends to underestimate wave energy which explains the lower than expected device performance. Furthermore, the PM spectrum is only validated for wind speeds of up to 20 m/s as few higher speed spectra were available in the original study [16]. Given the very low probabilities attached to the higher wind speeds the approach is believed to be reasonable.

Whether the frequency and intensity of storm activity has changed in the recent past or could be expected to alter with future climate change has been a popular area of study [20]. Evidence suggests that while regional averages over the Atlantic and Pacific show either no long-term change or a decrease in the total number of cyclones, there have been increases in the number of intense cyclones [21], suggesting larger extreme waves. More locally, storm frequency in the far Northeast Atlantic has increased since 1958, although the frequency appears to be lower since the early 1990s [20]. The changes in storm activity are mirrored by growth in extreme wave heights between 1958 and 1997: e.g., northwest of Ireland, winter extreme wave heights have grown by 0.5–1% per year [22]. Similar patterns have been identified in the mid-North Pacific where extreme wave heights have increased by 25–35% since 1950 [23]. Future extremes are also expected to increase: a current 20-year wave in the Northeast Atlantic would be expected to occur every 4 to 12 years by 2080 [24]. To ensure the development of the wave energy industry it will be crucial that WECs are rated to survive increasing extreme wave events.

Despite its limitations, this study has been a useful start in defining the extent to which wave energy conversion may be vulnerable to changing climate. More sophisticated approaches relating climate to wave conditions and driven by current and future climate as projected by GCMs will be necessary for detailed examination and the application of a range of analyses including scenario and risk analysis to this issue.

VIII. Conclusions

In common with other renewables, wave energy may be vulnerable to changes in climate resulting from rising carbon emissions. Despite a lack of a proven link to global warming, evidence indicates that wind and wave climates have altered over recent decades. Future changes will affect energy capture and ultimately plant economics.

In this study, a relatively simple sensitivity study uses changes in wind speed as a proxy for climate in order to quantify how wave energy production and economics could be affected by climate change

IX. Acknowledgements

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